Generation of High Speed Polarization Modulated Data using a Monolithically Integrated Device

Muhammad A. Naeem, Mohsin Haji, Barry M. Holmes, David C. Hutchings, John H. Marsh and Anthony E. Kelly

Abstract—**We report on the generation of high speed polarization modulated data via direct electrical binary data injection to the phase shifter section of a monolithically integrated laser diode integrated with a polarization controller. The device is fabricated on standard InP/AlGaInAs multiple quantum-well material and consists of a semiconductor laser, a passive polarization mode convertor and an active differential phase-shifter section. We demonstrate the generation of 300 Mbit/s Polarization Shift Keyed data.**

Index Terms—**Integrated circuit fabrication, Modulation, Phase shifters, Polarization.**

I. Introduction

THE ability to control and manipulate the state of polarization (SOP) of optical signals is becoming increasingly important as waveguide based optical communication systems progress towards faster data rates. Currently, such systems are assembled using bulk optical components such as waveplates, electro-optical modulators and polarizers. Various applications in areas such as integrated circuits, optical communication systems (based on dense wavelength division multiplexing (DWDM)) and semiconductor optical amplifiers (SOAs) should ideally be polarization independent to the incoming signals [1]. Photonic integrated circuits (PICs) provide the basis for replacing the manual alignment and assembly of multiple system components using lithography to combine multiple elements upon a single chip. This approach also provides a route to low cost and high production volumes with high yields. Furthermore, the miniaturization of devices allows for high speed and low drive voltage system requirements to meet the demands of current and future optical communications based applications. An important element in polarization modulation/control is the polarization mode convertor (PMC), which can be implemented as a modal evolution or as a mode beating element [2]. Mode beating provides the most compact solution, and various designs of mode beating PMCs have been realized and demonstrated in GaAs/AlGaAs [3], InP/InGaAsP [4] and silicon on insulator (SOI) [5] based material systems.

In this letter, polarization conversion is realized through mode beating in an asymmetric waveguide structure profile. This technique allows for polarization conversion in a shorter waveguide length than in any other adiabatic mode convertor [6]. Numerous devices with waveguide polarization functions can be realized around a universal mode beating PMC designed to provide 3 dB mode conversion in a half beat length (equivalent to a $\lambda/2$ waveplate with an optical axis at 22.5º or 67.5º to the wafer normal [2]). A polarization modulator can be realized by combining one or more PMC sections with Differential Phase Shifting (DPS) sections. These DPS sections provide birefringence in a symmetric waveguide and in principle, light can be converted from one polarization state into any other state [2] [7].

Conventional, lattice matched (unstrained) III-V semiconductor quantum-well (QW) heterostructure lasers, based on inter-band transitions predominantly emit transverse electric polarized light (TE) – i.e. light polarized along the plane of the wafer. This polarization dependence of the optical gain is due to quantum mechanical selection rules for optically induced transitions from the conduction band to the heavy hole valence band, which primarily select TE polarized light. We have previously reported a semiconductor Fabry-Pérot (FP) GaAs/AlGaAs laser with an integrated passive polarization rotator that is able to rotate the TE polarized output to the TM orientation [8]. The design and fabrication of which was later enhanced and included a passive PMC section and an active differential phase shifter section using strained InP/AlGaInAs MQW material, thus operating at a wavelength of 1550 nm [9]. In this article we report on the use of this device to produce Polarization Shift Keyed (PSK) data at speeds of up to 300 Mbit/s.

II. Design

The three section integrated device structure is shown in Fig. 1. A single PMC, 1.8 µm wide and 250 µm long (including 100 µm long trench), is placed between two active gain sections, which consist of a 2.4 µm wide, 700 µm long

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semiconductor laser and a 1000 µm long DPS section. Lateral taper sections of length 120 µm are used to reduce the loss in the transitions between the shallow and deeply etched waveguides. This includes tapers in the ridge waveguide width from 2.4 µm to 1.8 µm along with the shallow etched sections which also taper down to 1.8 µm from the 16.4 µm wide secondary mesas around the gain and DPS sections. These 16.4 µm wide regions are etched down to the etch stop layer at the top of the waveguide core. The deeply etched PMC also includes a 600 nm wide trench which is 300 nm from the edge of the waveguide [10], and is not electrically pumped, with a total length of 250 µm. Lateral tapers of 4 µm length are used at each end of the PMC trench to reduce interface losses. Furthermore, the reactive ion etching (RIE) lag phenomenon [12] [13] will serve to produce vertical tapering in the trench since its depth will vary with its width as it narrows towards the lateral taper end. The laser cavity is defined between the straight cleaved facet and a transverse deeply etched slot of 373 nm width prior to the PMC section and therefore the laser is effectively independent from the PMC and DPS sections.

The output waveguide is arranged to have a facet angle of 10º via a curved waveguide in order to reduce internal reflections and the possibility of compound cavity effects.

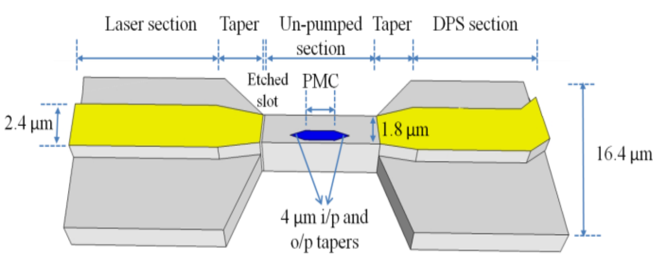

Fig. 1. Schematic of the semiconductor laser, with monolithically integrated sections labeled accordingly.

III. Fabrication

Precise control over the trench depth in the convertor sections is critical for the device to behave as required. This was achieved by utilizing the etch-stop layer, together with interferometric etch monitoring technique, resulting in the required run-to-run waveguide etching repeatability. The shallow-etched laser sections (i.e. etched to the top of the waveguide core) and trenches were fabricated using the RIE technique and the etch depth of the processed sample was measured (using a Dektek Profilometer) to be 1.912 µm. The deep-etched sections (i.e. etched down through the waveguide core) were fabricated using an inductively coupled plasma etching tool, resulting in measured depths of 3.676 µm. Here, the trench depth of 1.96 µm was obtained in the PMC. The PMC section was kept passive, whereas both sections on longitudinal sides of the PMC were kept active using the standard contact metallization technique. The SEM image of typical PMC in a waveguide is shown in Fig. 2.

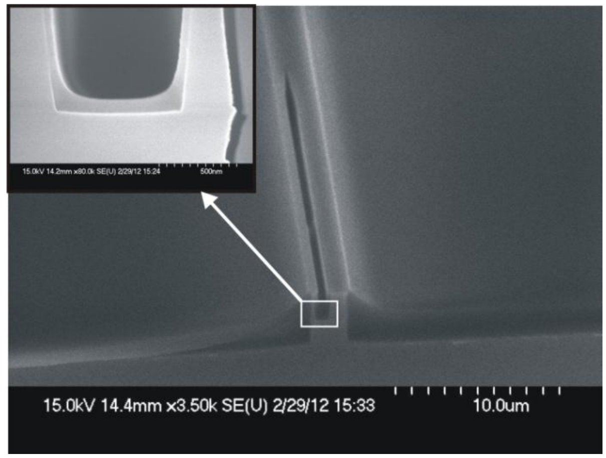

Fig. 2. SEM image of a typical PMC in a waveguide (inset shows the magnified cross-sectional view).

IV. Device Characterization

Fig. 3 shows the TE and TM polarized output power versus current from both facets of the device, as the DPS was biased to transparency to prevent effects from preferential TE absorption/amplification. As anticipated, the facet adjacent to the laser device emits predominately TE polarized light with the TM component substantially suppressed,. The output from the other facet shows almost equal TE and TM output indicating that the polarization was being converted in the PMC section into approximately equal TE and TM components, as expected; however, the output power at this facet was reduced due to the additional losses in the PMC and DPS sections, as discussed previously (previous paper).

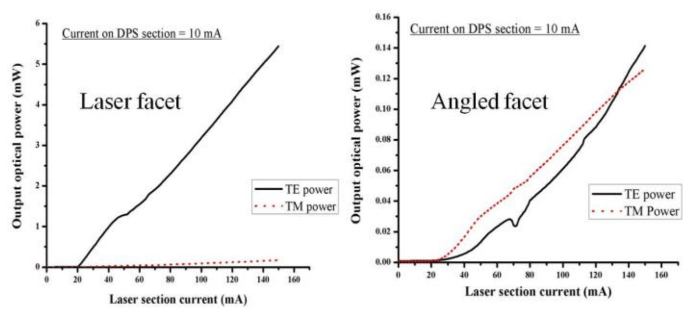

Fig. 3. Polarization resolved output power versus current for each of the device facets. The DPS section bias is 10 mA for each case. (Note: The output power was measured using a free-space wide-area detector)

These devices were characterized for polarization modulation by varying the current injection on the DPS section. Initial experiments with these devices demonstrated a minimum pulse width of 14.6 ns which was primarily limited by the electrical components used, which were unsuited for guiding the high speed signals efficiently through the chip.

In order to allow for high speed modulation, the device was mounted onto an Aluminium-Nitride tile with ground–signal-ground transmission line contacts printed with a titanium thin film resistor (43 Ω). The resistance of the DPS section was measured to be 7 Ω, thus when placed in series with the resistor along the transmission line, the total impedance was approximately 50 Ω, aptly matching the impedance of the RF circuit. The laser section of the device was biased using standard DC probes.

The polarization modulation behavior was characterized using CW electrical signals in order to ascertain the optimum bias point of the DPS section for data modulation. A constant current of 120 mA was applied to the laser section and the output power was measured as a function of bias voltage on the DPS sections, using a polarization analyzer at the device output set to +45° and -45° relative the plane of the wafer. This data is shown in Fig. 4, where it is apparent that the curves are the complement of one another, and also that in the range 1.3 V to 1.7 V there is little amplitude modulation associated with this change in voltage. Using a polarimeter, we measured this range equates to a 14^o polarization angle modulation. Outside of this range, the effect of the predominately TE gain (or loss) in the DPS section and losses in the passive PMC section will lead to unwanted changes in the TE/TM polarization ratio. The modulation depth of the polarization modulation in Fig. 4 is primarily limited by the PMC design, which can be improved by further optimization of the length and tapering.

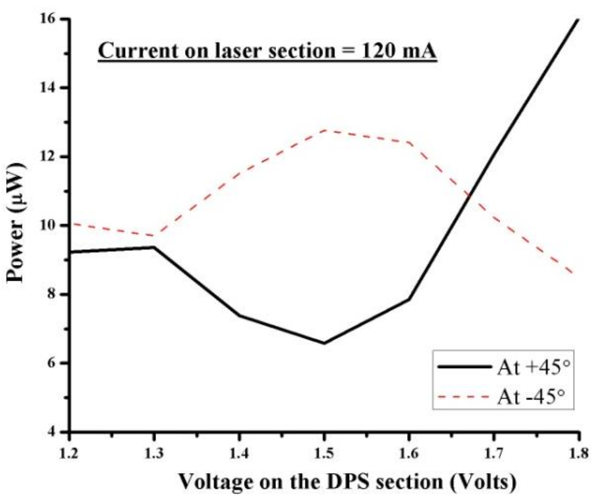

Fig. 4. Optical output power as a function of the voltage on the DPS section using RF probes for polarization angles of +45^o and -45^o. (Note: The output power was measured using a fibre-coupled high-speed detector).

The high speed polarization modulation behavior was characterized using the experimental arrangement shown in Fig. 5. A 300 Mbit/s NRZ signal was combined with a DC bias of 19.8 mA via a bias-T and was used to drive the DPS section of the device. The bias of 19.8 mA was found to be equivalent to the 1.5 V driving signal shown in Fig. 4. As before, a constant current of 120 mA was applied to the laser section.

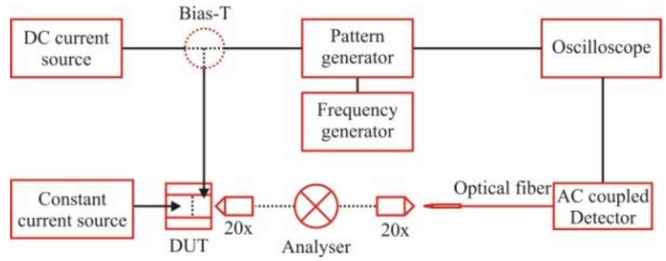

Fig. 5. A schematic of setup for measurement of response of polarization state after inducing binary input data.

The optical output was coupled into an optical fibre via two lenses and then connected to a commercial 2.5 GHz bandwidth coupled avalanche photodiode based photoreceiver. A polarization analyzer was placed between the two lenses allowing the temporal output to be viewed on the high speed oscilloscope for TE (vertical), TM (horizontal) -45° and +45° analyzer angles. A driving signal of 0.5 V peak-to-peak was found to be the optimum choice of NRZ signal amplitude, as anticipated from Fig. 4, taking into account some RF losses stemming from the bias-T, RF probe and across the ceramic Aluminium-Nitride tile to the device.

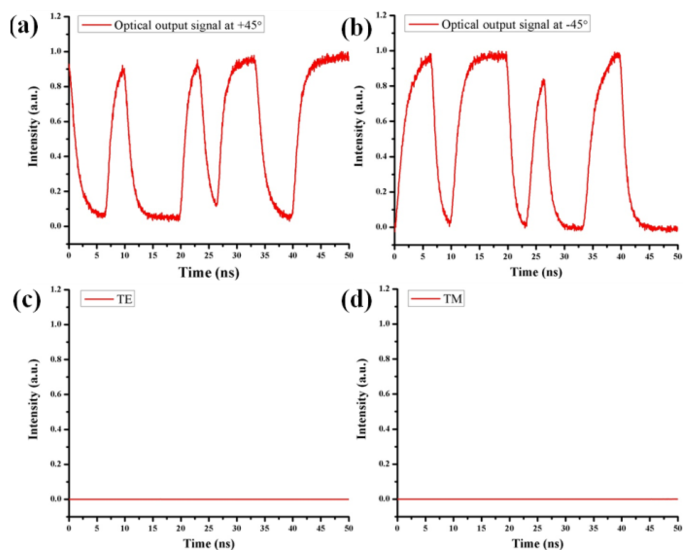

Fig. 6. Optical output signals measured for polarization angles of (a) 45º, (b)-45º, (c) 0º (TE) and 90º (TM)

Fig. 6 shows the temporal output in the form of averaged bit patterns from a real time oscilloscope. The outputs of the four polarization analyzer components are displayed on the same vertical and horizontal axes scale. As expected, the +45^o and -45^o data signals are consistent with the input electrical binary signal, and are the logical compliment of each other. The pure TE and TM outputs do not exhibit any signals, indicating that the amplitude of the TE and TM components are not being altered (only their relative phase is changed). It should also be noted that although the data appears to have a high extinction ratio due to the AC coupled receiver, the relatively modest values consistent with Fig. 4 are the best that we could achieve with this device.

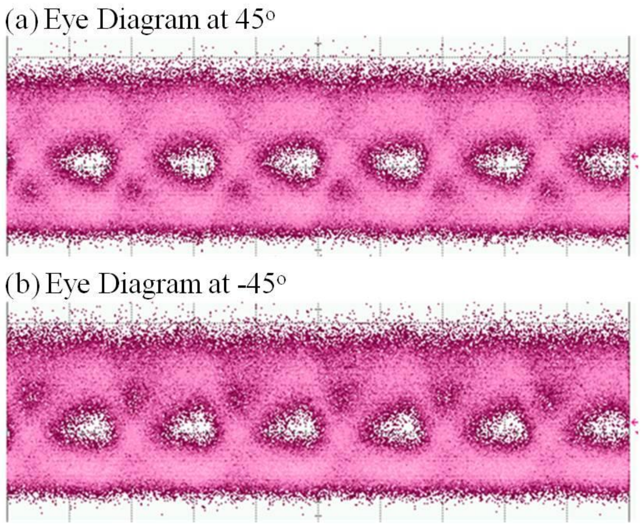

Fig. 7. Eye diagrams at 300 Mbits/s.

Fig. 7 shows the eye diagrams for operation at 300 Mbit/s for +45° and -45° measured on a sampling oscilloscope. The eye diagrams show some eye opening with no substantial differences in quality between the polarization analyzer angles. The relatively high levels of noise on the eye diagram are due to the low signal levels at the output of the device as indicated by the output powers in Fig. 4 and the resulting electrical amplification and instrument noise. It is, however, anticipated that this polarization modulation should reach data rates in the order of 1 Gbit/s for carrier injection, considering typical carrier lifetimes in this material [14]. In principle, using the quantum confined Stark effect, the modulation of the polarization could exceed 40 Gbit/s.

V. Conclusion

We have demonstrated a high speed polarization data modulator monolithically integrated with a semiconductor laser. The device consists of a FP laser, asymmetric waveguide polarization mode converter and a differential phase shifter section. Modulating the differential phase shifter section with a NRZ data signal produced a polarization modulated optical output with a small drive signal of only 0.5 V.

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Anthony E. Kelly biography is not available at the time of submission.